

SCALING NOMINAL SOLAR CELL IMPEDANCES FOR ARRAY DESIGN

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ABSTRACT

A methodology for estimating the AC impedance of solar arrays and in particular the Mars Pathfinder (MPF) cruise and lander solar arrays is presented. The MPF mission, cost and mass constraints, during an early stage of design, resulted in the proposed use of a gallium arsenide on germanium (GaAs/Ge) cell solar array for the cruise stage and a silicon, back surface field/reflector (SiBSFR) cell solar array for the lander. Previous work had shown that the AC impedance of silicon back surface field (BSF) cells was very different from that of non-BSF cells. There was immediate concern about how the difference in AC impedance would influence the design of the solar array shunt limiter circuitry and its operational stability. The findings are based upon the scaling of AC impedance measurements made on single cells and small solar cell arrays, and the use of a generic AC model to construct impedance equations used to determine the resistive and capacitive components of the cell impedance. Impedance data measured between 100 Hz and 100 KHz is presented for the proposed cells and small arrays. The data was obtained using dark forward biasing to simulate different toad points and intensities. Cell impedance tests show a large difference between SiBSFR and either Si non-BSF or GaAs/Ge cells, mainly because of the inherently high effective capacitance of the BSFR cells. Scaling rules were developed to assess solar array impedances from single cell and small solar array tests to characterize the MPF arrays, which in turn helped define power control circuit requirements.

INTRODUCTION

The MPF mission uses solar arrays in a direct energy conversion system for battery charging and as a primary power source. Due to mass and cost constraints, the same shunt limiter electronics will be used for power regulation on both the cruise and lander stages of the mission. Relatively large spacecraft power requirements near the end of cruise just prior to Mars entry, and limitations on lander mass further restricted the power

subsystem design. Other mission constraints include the use of fixed solar arrays with one week of direct sun pointing near Earth and a 40.6 degree off-sun attitude at Mars. The above constraints resulted in initial selection of a gallium arsenide on germanium (GaAs/Ge) cell solar array for the cruise stage and a silicon, 10 ohm-cm, back surface field/reflector (SiBSFR) cell solar array for the lander. Previous work [1] had shown that the effective cell capacitance of silicon back surface field (SiBSF) cells, increased with cell forward bias and was nearly 100 times greater than that of non-BSF cells. Previous work [2] also showed that solar cell impedance versus frequency characteristics are very much influenced by the solar cell diode current and capacitance. There was immediate concern about how the apparent difference in the AC impedance characteristics of the two cell types would influence the design and stability of a single shunt limiter circuit. A methodology for estimating the AC impedance of solar arrays in general, and more specifically the MPF cruise and lander arrays, is the main focus of this paper. In addition, attention is directed toward the unique AC impedance characteristics of the Silicon BSFR cells because it could influence the design of solar array shunt limiter circuitry.

ARRAY SPECIFICATIONS

During the early stage of the MPF solar array design, the GaAs/Ge cruise array had an operating range from 768 W at 74 C near Earth to 265 W at -30 C near Mars. The array consisted of 108 parallel strings and each string contained 41, series-connected, 2 X 4 cm cells. The estimated amount of wire in this array was 150 m, an average of 1.39 m for each string.

In addition, the MPF Si BSFR lander array had an operating range from 10 W at .90 C in the morning to a maximum of 174 W at 15 C around noon on the Mars surface. The array consisted of 41 parallel strings and each string contained 70, series-connected, 2 X 4 cm cells. The estimated amount of wire in this array was 120 m, an average of 2.93 m for each string.

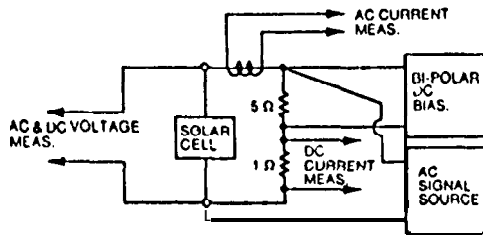


Figure 1. Dynamic Impedance Test Setup

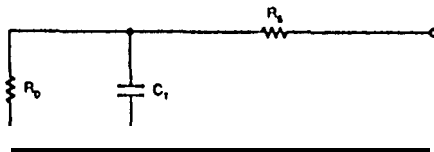


Figure 2. Generic AC Solar Cell Model

TEST DESCRIPTION

A dynamic impedance test setup, using dark forward voltage biasing (see Fig. 1) instead of illumination was used to make the AC impedance measurements. Great care was taken to minimize lead and resistor inductances and to eliminate ground loops in the test circuit. This method was chosen for test simplicity and because previous tests in our lab and earlier work [2, 3] show the dark AC impedance characteristics to be virtually the same as those conducted under illuminated conditions. The primary difference is that the voltage measured at the cell terminals is reduced by the voltage drop across the cell series resistance (R_s) when the cell is illuminated. The voltage drop applies for all load points and is calculated as follows:

$$V_{drop} = I_{sc} \cdot R_s \quad (1)$$

where:

I_{sc} = cell short circuit current while illuminated

DESIGN METHODOLOGY

Single 2 X 2 cm, Applied Solar Energy Corporation production solar cells, of the types considered for the arrays, were dark forward biased and the AC impedance curves of each type were measured for two families of cell diode current at selected forward bias voltages over a frequency range of 100 Hz to 100 KHz. The selected forward bias voltages were equivalent to near short circuit current (I_{sc}) condition, a range of anticipated load points for the solar array shunt limiter, and near open circuit voltage (V_{oc}) condition. Each of the curve families was designed to be equivalent to specific mission solar intensities and cell temperature. Due to equipment limitations, the lowest

cell temperatures used were not those expected during the mission, and only provided limited data on temperature effects. Phase angle measurements were also made in conjunction with the AC impedance measurements. This allowed the AC impedance measurements to be separated into their component parts.

Small arrays consisting of 4 series cells of the same types were then dark forward biased at 4 times the voltage, resulting in nearly the same cell diode current as measured for the single cells. Otherwise, the families of AC impedances, together with the phase angle measurements, were measured under the same test conditions. The single cell data was compared to the small array data to provide some confidence in a scaling methodology and to study the effect of the high capacitance of the Si BSFR cells. A generic AC model of a single cell (see Fig. 2) was used to construct impedance equations which were used to calculate the resistive and reactive components of cell impedance at the f_{3dB} breakpoint on the AC impedance curves as follows:

$$R_T = R_0 + R_s = Z / \cos \phi \quad (2)$$

$$C_t = \sin \phi / 2\pi f Z \quad (3)$$

Where:

R_t = total cell resistance

C_t = total cell capacitance

Z = measured AC impedance @ 100Hz

$f = f_{3dB}$, where Z has decreased by 3dB

ϕ = phase angle @ f_{3dB} , typically 45°

R_s = cell series resistance, typically < 1 ohm

R_0 = cell diode resistance

Since R_s is small and R_0 is dominant at the f_{3dB} breakpoint on the AC impedance curves,

Then:

$$R_0 \approx Z / \cos \phi \quad (4)$$

Relating to impedance versus frequency plots, the breakpoint is found by:

$$(2\pi f)_{3dB} = 1 / (R_0 C_t) \quad (5)$$

Values of $R_0 \approx Z$ at the low frequency limits of the AC impedance curves (see Figures 3 through 6), The 1 and V shown for each curve correspond to the values of cell diode voltage (V_D) and diode current (I_D) used during AC impedance measurements, except that the values of V are the result of increasing the actual values of V_D by V_{drop} (eq.

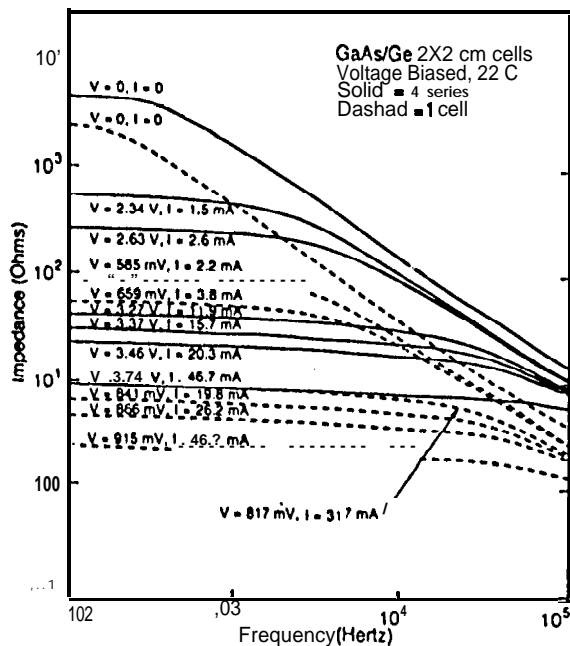


Fig. 3 AC Impedance vs. Frequency for 4cm² GaAs/Ge Solar Cells at 22 C,

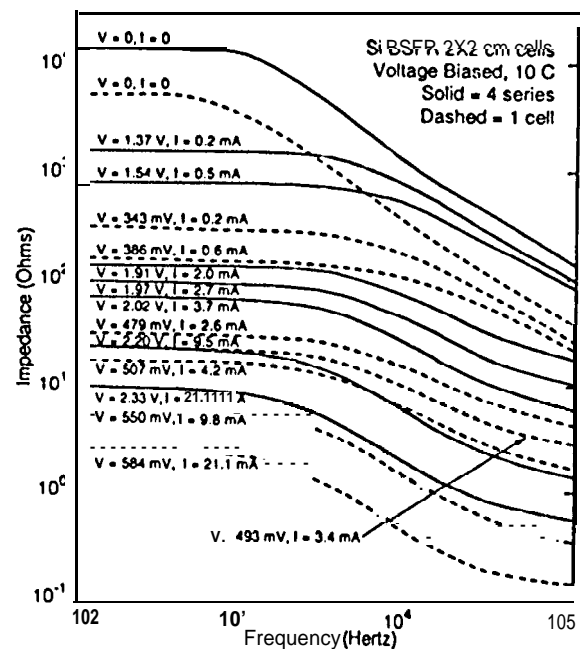


Fig. 5 AC Impedance vs. Frequency for 4cm² Si BSFR Solar Cells at 10 C.

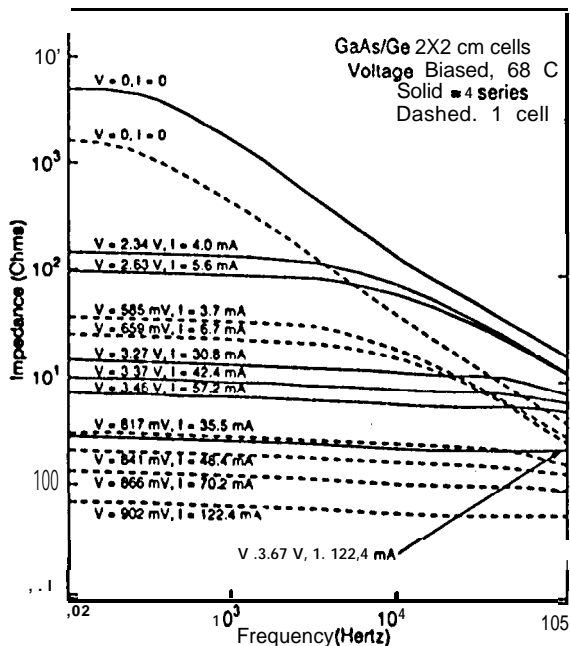


Fig. 4 AC Impedance vs. Frequency for 4cm² GaAs/Ge Solar Cells at 68 C.

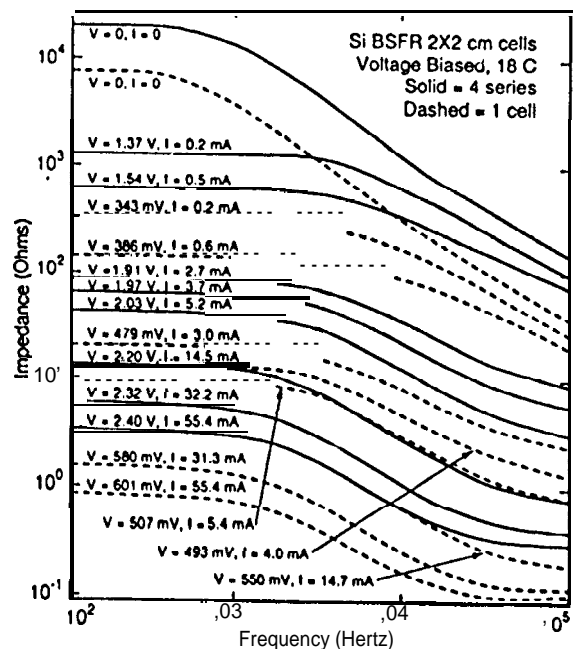


Fig. 6 AC Impedance vs. Frequency for 4cm² Si BSFR Solar Cells at 18 C.

1) 10 provide a direct comparison to anticipated load points when illuminated,

When R_0 decreases due to increased I_0 , then the breakpoint will increase proportionally if C_1 is constant. For example, if a family of curves shows no change in the breakpoint, then C_1 is rapidly increasing. The f_{3dB} breakpoints for a family of AC impedance curves is therefore a convenient means of tracking the behavior and value of C_1 where I_0 and its corresponding V_0 is being increased,

RESULTS

The families of impedance data for the GaAs/Ge cells and for the Si BSFR cells are presented as graphs (see Figs. 3 through 6). These graphs show a notable difference between the AC impedance characteristics of the Si BSFR and the GaAs/Ge cells, mainly due to the inherently high capacitance of the Si BSFR cells. The dominant feature of the impedance curves is the behavior with increasing frequency. The GaAs/Ge data (see Figures 3 and 4) shows the f_{3dB} breakpoint (eq. 5) increasing as the AC impedance is decreasing due to corresponding increases in cell I_0 and V_0 . Calculations show that this behavior is the result of a cell capacitance change from about $0.5 \mu F$ to only about $1 \mu F$.

The Si BSFR data (see Figures 5 and 6) shows that the f_{3dB} breakpoint increases somewhat as the impedance is decreasing, but only for low values of cell I_0 and V_0 . When I_0 and V_0 are further increased, the f_{3dB} breakpoint (eq. 5) begins to decrease. This behavior indicates a marked increase in cell capacitance. Calculations show that this behavior is the result of a cell capacitance change from about $0.1 \mu F$ to as high as about $100 \mu F$.

All but the AC impedance curves obtained for an I_0 and V_0 of zero, for each of the curve families, had a worst case impedance ratio of $4.0 \pm 20\%$ and a worst case capacitance ratio of $0.25 \pm 5\%$ when the 4-series cell data was compared to that of the single cells. The curves resulting from an I_0 of c 2 mA had the worst case errors. The error for data taken when I_0 and V_0 equaled zero was considerably higher. This is apparently due to measuring the AC impedance at 4-times multiples of V_0 rather than matching I_0 , which has the primary influence on cell AC impedance. In addition, no attempt was made to match the cell $I-V$ characteristics, therefore some variation in cell AC impedance would be expected, particularly when making measurements at zero I_0 and V_0 where the individual cell R_0 will vary considerably.

CONCLUSIONS

The results of the tests confirm that the generic AC solar cell model (see Figure 2) can be directly scaled to a full sized array, assuming that all cells are identical and cell

interconnections and cabling are negligible. Clearly, for this case one can make AC impedance measurements on the basic element, the solar cell, and only consider the number of cells in each series string and how many parallel strings there are in the array. However, in reality the cells in an array are not identical. Therefore the results of scaling up from a single cell AC impedance characteristic must be considered as approximate. This is particularly true for low values of cell I_0 where the impedance could be in error by perhaps $\pm 50\%$. One must also consider the effect of series inductance in the array strings and cabling, and how it can be reduced. The inductance of the 2.93 meters of wire used for each of the paralleled strings in the proposed Si BSFR lander array could result in about $0.15 \mu H$ of array series inductance. The inductive reactance would be about 0.1 ohms, canceling the array capacitive reactance at a frequency of about 100 KHz and an array voltage of 36 volts at Mars noon solar irradiance. When the solar irradiance is greater or less than this, the reactive component of the array impedance would swing from capacitive to inductive, respectively. These scaling rules, developed to assess solar array impedance characteristics from single cell measurements, were used for characterizing both of the proposed MPF arrays. This, together with information on the unique character of the Silicon BSFR cells, helped define power control circuit requirements. Similar AC impedance and phase angle data was obtained for additional types of cells including InGaAs and Si Back Surface Reflector (BSR) cells and a JPL Publication is planned for 1995 wherein this additional data will be presented and discussed.

ACKNOWLEDGEMENT

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